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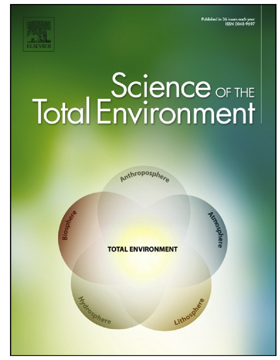

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Evaluating natural infrastructure for flood management within the watersheds of selected global cities

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Abstract

Cities are dependent on their upstream watersheds for storage and gradual release of water into river systems. These watersheds act as important flood mitigation infrastructure, providing an essential ecosystem service. In this paper we use metrics from the WaterWorld model to examine the flood management-relevant natural infrastructure of the upstream watersheds of selected global cities. These metrics enable the characterisation of different types, magnitudes and geographical distributions of potential natural flood storage. The storages are categorised as either green (forest canopy, wetland and soil) or blue (water body and floodplain) storages and the proportion of green to blue indicates how different city upstream basin contexts provide different types and levels of storage which may buffer flood risk. We apply the WaterWorld method for examining flood risk as the ratio of accumulated modelled annual runoff volume to accumulated available green and blue water storage capacity. The aim of these metrics is to highlight areas where there is more runoff than storage capacity and thus where the maintenance or restoration of further natural infrastructure (such as canopy cover, wetlands and soil) could aid in storing more water and thus better alleviate flood risks. Such information is needed by urban planners, city authorities and governments to help prepare cities for climate change impacts.

Keywords: flood storage; ecosystem services; green infrastructure; land-use change; protected areas, WaterWorld

Introduction

Cities depend on their surrounding peri-urban and rural ecosystems for a variety of ecosystem services, in particular, flood regulation and control. This is the ecosystem's capacity to reduce flood risk or disturbance thereby providing a regulating service and benefit of enhanced safety to human life and human constructions (de Groot et al., 2002). Flood risk results from heavy or prolonged precipitation events leading to reduced infiltration into the soil and increased surface runoff across the land surface into surface waters (streams, rivers, lakes and reservoirs). Lowering flood risk is generally achieved by reducing the surface runoff volume through i) increased infiltration into the soil, ii) storage (in either natural or built infrastructure), and iii) slow release of water by canopies, water bodies, soil and aquifers. Ecosystems can regulate floods by *preventing* their occurrence, such as by redirecting or absorbing precipitation, reducing surface runoff and river discharge; or *mitigating* their impact by providing retention space for surplus water and thereby lowering flood volumes and destructive power (Nedkov and Burkhard, 2012).

The ecosystem service of flood regulation (prevention and mitigation) is of growing importance due to the projected increases in frequency, intensity and duration of extreme precipitation events under current and future climate change (Frei et al., 2006; IPCC, 2014; Rao et al., 2014; Revi et al., 2014) and due to increased exposure of increasingly valuable assets in urban areas near to rivers.

Ecosystem services are, by definition, a function of supply and demand (there is no service without demand for it). Urban areas, and in particular cities, are high *demand* areas for the flood regulation service due to high concentrations of people and infrastructure, and for their tendency to be in low-lying areas close to river crossings and fertile agricultural lands. Despite this demand for the service, urban areas are disadvantaged in that flood regulation services are particularly sensitive to increases in agriculturalisation, urbanisation, and subsequent loss of relevant ecosystems (Chin, 2006; Eigenbrod et al., 2011; Hunt and Watkiss, 2010). The hydrological impacts of urbanisation result from a reduction in perviousness resulting in reduced infiltration and surface retention, thus increasing the proportion of storm rainfall that goes to runoff, leading to larger and more frequent floods. However, floods affecting urban areas can either be generated locally or elsewhere in the watershed; it is therefore important to consider the role of ecosystems not only within the urban areas themselves, but in the entire landscape of the watershed (Depietri et al., 2012). Indeed, the *supply* of the flood regulation service, which either prevents or mitigates floods, will mostly be generated by ecosystems upstream of the urban areas. For this reason, in this study we focus on the river basins (watersheds) upstream of our cities of interest.

Measuring and mapping flow regulation as an ecosystem service

Measuring and mapping ecosystem services usually requires identifying an indicator or proxy that represents the service. Key environmental variables that impact rainfall-runoff responses include 1) the physical characteristics of river catchments, particularly altitude and slope; 2) variation in evapotranspiration rates, vegetation-soil interactions and modifications of the surface roughness across different land cover/land use types; and 3) soil hydraulic properties such as infiltration capacity and the water holding capacity (WHC) of the soil. The onset, duration and magnitude of a flood hazard are highly dependent on precipitation intensity, duration and extent, creating different flood types (e.g. rain based fluvial (river) floods, pluvial (rainfall-generated overland flow from high-intensity rainfall) floods, snowmelt-fluvial floods. The flood regulative effect of the above mentioned environmental variables may, therefore, depend considerably on the precise characteristics of the underlying precipitation event and prior weather conditions (Stürck et al., 2014). The consideration of all these different factors alongside the role of topography in determining where will be inundated makes flood modeling complicated and onerous, requiring many input datasets and specific skills. Even then the results may not be very accurate or informative.

Applying an ecosystem services approach allows us to focus on mapping the supply of the service versus the potential demand for the service. Areas where service capacity is exceeded and therefore compromised will help pinpoint where action is needed. Several studies have mapped flood regulation/ mitigation within the ecosystem services framework. These studies tend to examine multiple ecosystem services simultaneously, use a wide range of indicators from land cover/land use types, to biophysical factors such as slope and elevation, and consider many spatial scales.

For example, Chan et al. (2006) in their regional study explored the trade-offs and opportunities for aligning conservation goals for biodiversity with six ecosystem services in California. For the flood control part of the study, their model identified the areas important for maintaining a natural flooding regime and reducing the risk of extreme flood events attributable to impervious surfaces in a watershed. The feature value in the model varied with land cover in various categories and distance to the floodplain to reflect the flood-mitigation contribution of vegetation in floodplains, wetlands, the riparian zone, and beyond (Chan et al., 2006). Tratalos et al. (2007) looked at a bundle of ecosystem services along a rural-urban gradient in five UK cities. To measure surface water runoff they used the SCS-CN method which calculates the maximum potential rainfall retention of the catchment based on the soil type and land cover for a specific storm event (Tratalos et al., 2007). Egoh et al. (2008) in a study to develop national-scale maps of selected ecosystem services in South Africa used groundwater contribution to surface runoff as the most direct measure of the water regulation function of a catchment. Data on the percentage contribution of groundwater to baseflows were obtained per quaternary catchment and expressed as a percentage of total surface runoff (Egoh et al., 2008).

Studies focusing solely on flood regulating services are rare. Nedkov and Burkhard (2012) claim to have conducted one of the first ecosystem service assessments exclusively focusing on flood regulating ecosystem services at a landscape scale. They examined water retention functions of vegetation and soil cover and modelled peak river flows and land cover types for a river basin in Bulgaria, mapping both supply and demand for the service. Stürck et al. (2014) also focused only on flood regulation services but at the continental scale of Europe. They estimated the effects of five environmental variables (catchment type, precipitation types, catchment zone, soil water holding capacity and crop factor) on discharge volumes following precipitation events. These studies required complex data inputs, often at the local or regional scale, making it difficult and onerous to replicate for other sites and allow cross-comparison.

In response to this challenge, we apply recent metrics developed and documented by Mulligan (2016) as part of the WaterWorld Policy Support System. These metrics utilise the ecosystem service approach by distinguishing between the potential service (as the storage volume) and the realised service (the storage volume in relation to the volume of storage required to house the annual runoff). WaterWorld uses in-built global datasets, thus minimising user input and need for expert skills, and allowing for standarised comparisons. It can also be applied for any terrestrial site on the globe at either 1ha or 1km^2 resolution.

Natural Flood Storage and Natural Flood Management

Typical approaches to flood management have relied on ‘hard’ engineered solutions involving ‘grey infrastructure’. In recent years there has been a move to use green infrastructure, or “nature-based solutions” which either use or are inspired by natural processes. These interventions can be completely “green” (i.e. consisting of only ecosystem elements) or “hybrid” (i.e. a combination of ecosystem elements and hard engineering approaches). Nature-based solutions aimed at mitigating flood risk are referred to as “nature-based flood protection” (World Bank, 2017) or “natural flood management”.

Natural flood management (NFM) refers to strategies and practices to utilise or restore ‘natural’ land cover and channel-floodplain features within catchments, by storing or slowing down flood waters in order to increase time to peak flow and reduce flood peak (SEPA, 2013). NFM has gained a lot of attention recently, particularly in policy agendas across Europe, as it is recognised as a means to reduce flooding whilst delivering a wide range of other benefits, such as biodiversity, water quality, recreation and resilience to climate change (Iacob et al., 2014; SEPA, 2013).

Understanding how catchments store water can yield important insights into how catchments release water (McNamara et al., 2011). In our study we use estimates of the water storage capacities of canopy cover, soil, wetlands, floodplains and water bodies as the components of natural ‘green’ infrastructure relevant to mitigating flood hazard to downstream cities. We refer to these landscape components as ‘natural flood management infrastructure’. We have not used groundwater since this is a store that contributes directly to river baseflows and thus flood peaks. It is also not a storage capacity that is subject to reduction as a result of land use and management.

Forests and other vegetation types (canopy cover in the WaterWorld model) reduce runoff through i) enhanced *infiltration* via their root networks which increase soil macroporosity, and by ii) *interception* of rainwater by temporarily storing it on surfaces, such as leaves, branches, trunks, and stems of trees, as well as on the herb and litter layer, and evaporate it back into the atmosphere, such that it never reaches the ground (Attarod et al., 2015). Canopy water storage capacity thus refers to that temporary store of water from interception, defined as the amount of water left on a saturated canopy when evaporation is negligible, and rainfall and canopy drainage has ceased (Attarod et al. 2015). The tree structure, type of species, climatic factors, and rainfall intensity are known to control the size of canopy water storage capacity. Forests and vegetation also contribute to water loss more directly through transpiration where water is taken up by the plants and subsequently lost through leaf surfaces to the atmosphere. These losses occur on different time scales; for example, canopy interception loss is relevant during and immediately after a storm event, while transpiration plays a role in managing soil moisture in the days or weeks between storm events (Berland et al., 2017).

Due to this important role of forests and canopy cover on the hydrological cycle, forest loss (deforestation) is considered to exacerbate the impact of floods by increasing runoff due to reductions in the interception of rainfall and the evaporation of water from the tree canopy, coupled with reductions in the infiltration rate of soils (Bradshaw et al., 2007). Conversely, afforestation (foresting a previously unforested area, or reforesting a deforested area) is considered to be a significant strategy for NFM. For these reasons, several flood-affected nations like Costa-Rica, China, India, Nepal and Bangladesh have invested heavily in forest protection or reforestation (Laurance, 2007) and the UK is conducting many NFM-based planting experiments; though there has also been some criticism of this 'flood and forests' discourse (see FAO-CIFOR 2005; Calder and Aylward 2006).

Soil aids flood regulation through infiltration and storage with different soil types having different capacities to store moisture, depending on their particle size distribution, porosity, level of compaction, soil depth, organic content and other factors. Coarser, sandier soils will have greater infiltration capacity and therefore prevent runoff that can exacerbate flash floods, but soils with greater levels of silt and clay (and therefore a higher surface area of particles) have greater water retention capacity once the water has entered the soil.

Floodplains, wetlands and waterbodies such as lakes and reservoirs aid flood regulation mostly through their storage function. However, floodplain 'roughness' can also affect the rapidity of flow (known as conveyance) (, so that the more 'rough' or disrupted the floodplain the slower the runoff. Riparian woodlands and wetland vegetation provide important flood regulation services by acting as a roughness element to surface water flow, slowing the water down and helping to prevent it entering the channel too rapidly, as well as through the usual evapotranspiration processes of vegetation. Riparian zones also help to store water on upstream floodplains during flood conditions, mitigating impacts downstream.

Flood potential metrics utilising water storage capacities of natural infrastructure

Our study applies the WaterWorld realized flood mitigation index which highlights areas where there is more downstream cumulated annual surface runoff than downstream cumulated surface water storage capacity. This indicates where there is potential for overtopping of storage, and thus flooding, on an annual basis. Upstream of these areas can be targeted for maintenance or installation of further natural infrastructure (such as improved canopy cover, wetlands and soil) to aid in storing more water and thus better mitigating flood risk. They can also be considered of high risk, and assets to be insured and adapted accordingly.

We demonstrate the use of natural infrastructure flood metrics that are globally applicable and require low-data inputs (fully described in Mulligan 2016) for the upstream basins of five global cities: Chennai, Jakarta, Bogotá, London, and Guayaquil, by 1) mapping the magnitude and types of 'natural' storages in these basins, 2) determining how much of this storage is found in protected areas (and thus possibly less likely to be negatively impacted by land use change) and upstream of/near to urban areas (and thus possibly more at risk), and 3) using the WaterWorld realised flood mitigation metric (which compares accumulated annual runoff to storage capacity) to determine areas of potential annual flood risk. The aim is to highlight areas that are providing flood mitigation services and to understand which may be at risk from changes in land-use and land-cover management.

Materials and Methods

Study areas

Two inland city upstream basins (Bogotá in Colombia and London in the UK) and three coastal city upstream-basins, (Chennai in India, Guayaquil in Ecuador and Jakarta in Indonesia), were selected representing a mix of continents and climatic conditions. The size of their upstream basins also vary, as do the size and characteristics of the cities themselves: four of the cities (London, Bogotá, Chennai and Jakarta) are considered “very large”, with over 8 million people, and one, Guayaquil, is considered “medium” sized, with 2.7 million people (United Nations, 2018). We deliberately chose a very diverse set of basins to apply this method in order to better understand the variety of green infrastructure and flood-risk contexts. Our intention was not to validate the WaterWorld metrics, but rather to apply them in contexts of low data availability and compare findings between city-basin contexts to explore the range of outcomes.

Hydrological model

We chose to use metrics from the WaterWorld (V2) hydrological model as it uses in-built global datasets thus requiring no data inputs from the user and enabling standarised comparisons across disparate basins and regions. WaterWorld (Mulligan, 2013) is a fully distributed, process-based hydrological model that utilises remotely sensed and globally available datasets to support hydrological analysis and decision-making at national and local scales across the globe. The model includes modules for rainfall distribution based on wind interaction, fog inputs based on cloud cover and potential and actual evapo-transpiration based on climate and vegetation cover (MODIS Vegetation Continuous Fields; Sexton et al. 2013; Hansen et al. 2006). Runoff is calculated as the downstream accumulation of water balance along a drainage network calculated from a digital elevation model. The model’s equations and processes are described in more detail in Mulligan & Burke (2005), Mulligan (2013) and Mulligan (2016). The model parameters are not routinely calibrated to observed flows as it is designed for application in low data environments and for hydrological scenario analysis using a physically-based model. (Mulligan, 2013). WaterWorld (V2) was used at 1-km spatial resolution.

Selection of upstream catchments

WaterWorld, was used to delineate basin boundaries by selecting points on watercourses upstream of the city region, resulting in a study basin containing the entire upstream basin before it enters the main urban area. WaterWorld uses a D8 routing algorithm and the HydroSHEDS flow network (Lehner et al., 2006) applied at 1km spatial resolution for this analysis. For some cities with extensive sprawl or abutting urban areas, determining the limit to the city extent was problematic. Upstream points were chosen outside the most dense part of the city or near the boundary of the urban extent using the MODIS Urban Land cover 500m dataset (Schneider et al., 2009). Figure 1 shows the basin extents in relation to the urban areas and major rivers. We deliberately excluded the city from the basin for a number of reasons: 1) the natural infrastructure that we are interested in, is in the upstream, rural catchment, not in the city; 2) green infrastructure in the city is fairly small scale and primarily provides different services to those under investigation here and little opportunity for further investment given urban land prices and constraints; 3) WaterWorld is not an urban hydrological model so does not model urban drainage infrastructure. However, we acknowledge that the level of development in different basins will mean that the rural and peri-urban areas will have different levels of drainage via infrastructure. WaterWorld cannot model tidal flows, so for London specifically, an area upstream of the tidal reach of the Thames (Teddington Lock in the west of London) was used as the basin outlet. The level of development in different basins will mean that the rural and peri-urban areas will have different levels of drainage via infrastructure.

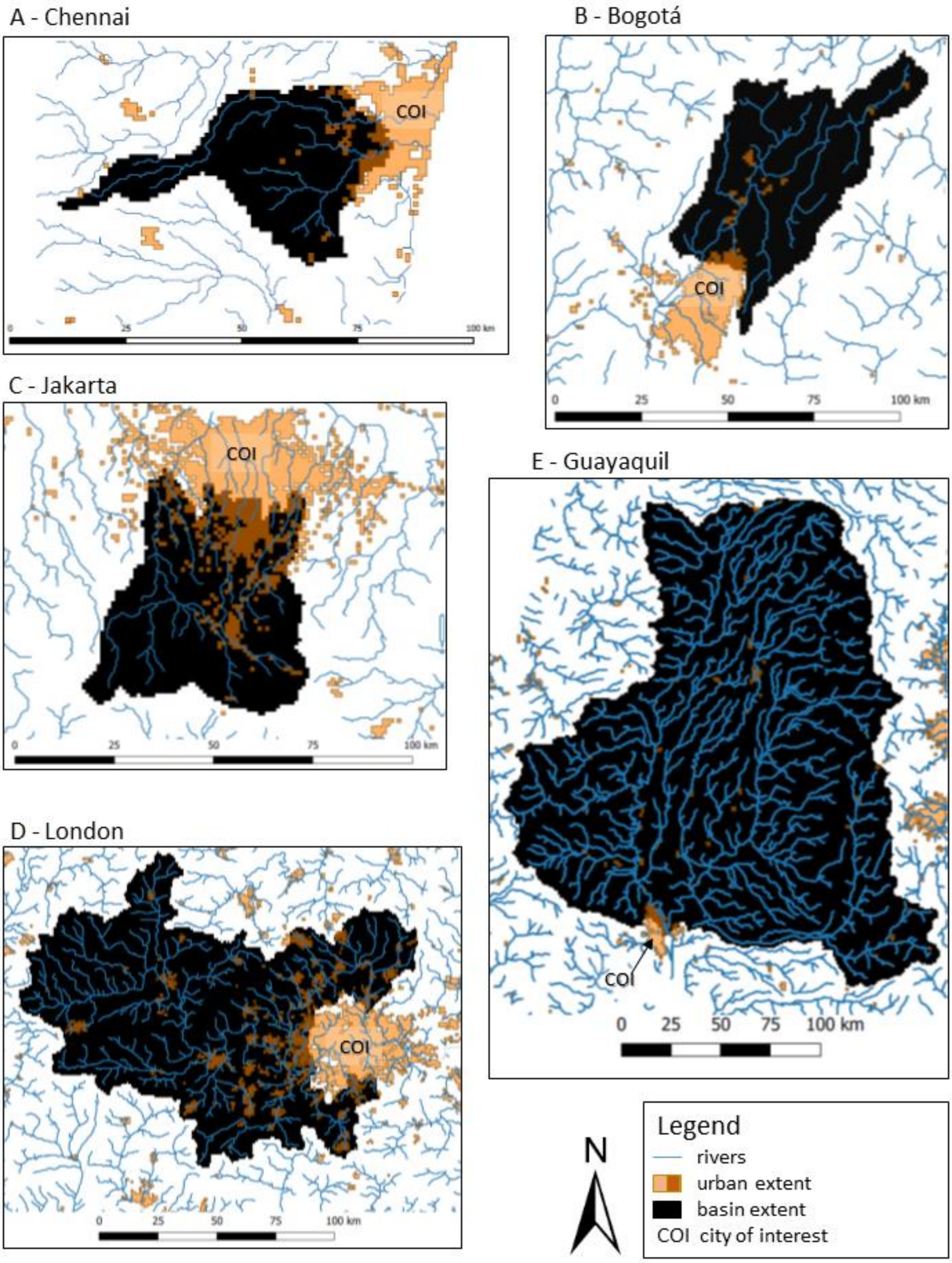

Figure 1. Study areas showing the basin extents upstream of five cities, A) Chennai, B) Bogotá, C) Jakarta, D) London, E) Guayaquil.

Natural-infrastructure metrics

Mulligan (2016) describes a range of new metrics for natural flood storage infrastructure based on analysis of remotely sensed data and hydrological modelling and delivered as part of WaterWorld. These include the floodplain storage capacity; water body storage capacity, wetland storage capacity, canopy storage capacity, soil storage capacity, and the total storage capacity. Each can be calculated globally from a range of remote sensed data at 1km spatial resolution on a per grid cell basis and can be accumulated down a surface flow network. They can be calculated for all areas or just for areas that are 'protected' according to the World Database of Protected Areas (WDPA) (IUCN and UNEP-WCMC, 2015) for example. In this way, flood-risk-relevant natural infrastructure can be mapped in terms of the areas supplying the associated ecosystem service (water storage), the accumulation of that service downstream and the volume of the service that is 'secured' within the boundaries of protected areas.

Total natural storage capacity includes floodplain, wetland, canopy, water bodies and soil components. Wetland, canopy and soil stores are considered together as "green" storage capacity since they are at least in part a function of land cover and use and thus can be managed through conservation interventions. Floodplain and water bodies are considered "blue" storage since they are a function of landscape properties such as topography, and the least susceptible to human modification or management. Although floodplains can be built on, their flood storage capacity remains and cannot easily be modified.

The ecosystem service value of natural flood management infrastructure depends upon the relationship between the supply of the potential service (the storage capacity in use) and the demand for the service (the potential service that is upstream of infrastructure or populations and thus realised). In this analysis we use the WaterWorld realised flood mitigation metric which is calculated as the ratio of runoff (downstream accumulated precipitation excess) to storage capacity (total volume of green and blue storage). Where this ratio is greater than 1 there is, in an average hydrological year, more water flowing through a grid cell than the storage capacity to store it, and the excess water may thus overspill from the stores (which include rivers themselves as part of the water body layer) and represent a flood risk. Where the ratio is less than 1 there is a greater capacity to store surface water than there is runoff flowing through these stores annually, so flooding will be less likely. We calculate these service ratios separately for total storage capacity, green storage capacity and blue storage capacity in order to better understand which stores contribute most to mitigation of flood risk. Each metric is described fully in the WaterWorld V2 documentation (Mulligan, 2016) but a short summary is provided below.

Floodplain storage capacity

Floodplains are defined in WaterWorld using a combination of Strahler stream orders and elevation (details in Mulligan 2016). The average height of water storage capacity on a floodplain can be set by the user but for this analysis the default of 0.5m was used.

Water body storage capacity

Water body storage is calculated based on the full grid cell surface water frequency dataset of Mulligan (2013). The area of each water body is calculated and the volume of estimated based on the empirical relationship of Lehner et al. (2011). Seasonally dry grid cells (usually those around the edge of a water body) are considered to have lower storage capacity than those that are permanently wet and thus considered to be deeper.

Soil storage capacity

Soil storage capacity is a topographic metric based on a topographic index-scaled soil depth for all non-impervious surfaces. It thus represents porous soil storage capacity. Soil thickness is scaled between 0 and a user defined maximum accessible soil thickness (set to 2.0m by default) linearly according to the calculated topographic wetness index (Beven and Kirkby, 1979). In addition to the topographic effect, vegetation is also considered to influence soil thickness with a user-specified thickness of soil added for each per-cent of tree cover (set by default to 1mm, which gives 10cm extra soil thickness at 100% tree cover). Finally, where water bodies, urban areas or roads exist, soil storage is considered inaccessible. For water bodies it is set to zero, for roads the fraction of the grid cell occupied by the road is considered inaccessible and for urban areas 90% of the soil storage is considered inaccessible (the remaining 10% representing green surfaces in the urban matrix).

Canopy storage capacity

Canopy storage capacity is calculated on the basis of the percentage tree cover in each grid cell and a closed canopy storage capacity per rainday set to 5mm, the mid-point of the range proposed by Davies-Barnard et al. (2014), who present values for trees varying from 0.1-9.1mm across arid, temperate and tropical regions. 5mm is thus considered a representative average for a closed canopy. In order to account for interception losses, a rain per rain-day metric is calculated from the precipitation (Hijmans et al., 2005) and raindays layers (Cramer and Leemans, 2001). Where rain per rain-day is greater than the storage capacity of a grid cell the storage capacity is used, if less than the storage capacity, the available rain per rain day is used. This is thus a metric of the storage capacity available for a given rainfall event.

Wetland storage capacity

Wetland storage capacity is based on the part grid cell surface water frequency dataset of Mulligan (2013). The volume of storage per grid cell is calculated from the surface wetness frequency multiplied by a mean wetland depth set to 5.0 metres by default. In this way surface wetness frequency is assumed to indicate the proportion of the grid cell available for water storage. This variable tends to capture water storage capacity at the edges of permanent water bodies and in seasonally drying wetlands.

Total storage capacity

Total storage capacity is by default comprised of floodplain storage capacity, wetland storage capacity, canopy storage capacity, soil storage capacity and waterbody storage capacity.

Accumulated storage and ratios of runoff to capacity

Storage capacity is only significant to downstream areas when there is sufficient rainfall to fill those stores. Where there is little or no rainfall, flood storage capacity will be of little relevance. The WaterWorld realised flood mitigation service is thus the ratio of runoff to water storage capacity. This assumes that if there is sufficient storage to store the total annual flow, that flood risk (outside of these stores) will be minimal since they will provide the buffering capacity to store the flows. This is simplistic in that it ignores the event basis of many floods and the role of antecedent filling of stores in creating risk. Nevertheless, for spatial comparisons of mitigation of flood risk, it is useful. Runoff in WaterWorld is the downstream accumulation of water balance (rainfall+fog+snowmelt minus actual evapotranspiration) derived from global datasets (Mulligan 2013). The runoff is divided by the corresponding storage capacity and where the ratio is greater than one, the volume of water present is in excess of the capacity to store it either on a grid cell or downstream cumulated basis.

Figure 2 illustrates this concept of natural storage being overtopped creating runoff that cumulates downstream. It shows a schematic of grid cells (1ha x 1ha or 1km x 1km land parcels used by the WaterWorld model) containing different storage types with different capacities of water volume that they can hold. If more water is input into the grid cell than the total capacity to store it, then the water will continue downstream. The ratio of downstream cumulated surface water (runoff) to surface water storage capacity is thus a measure of the extent to which the stores are full or over-full.

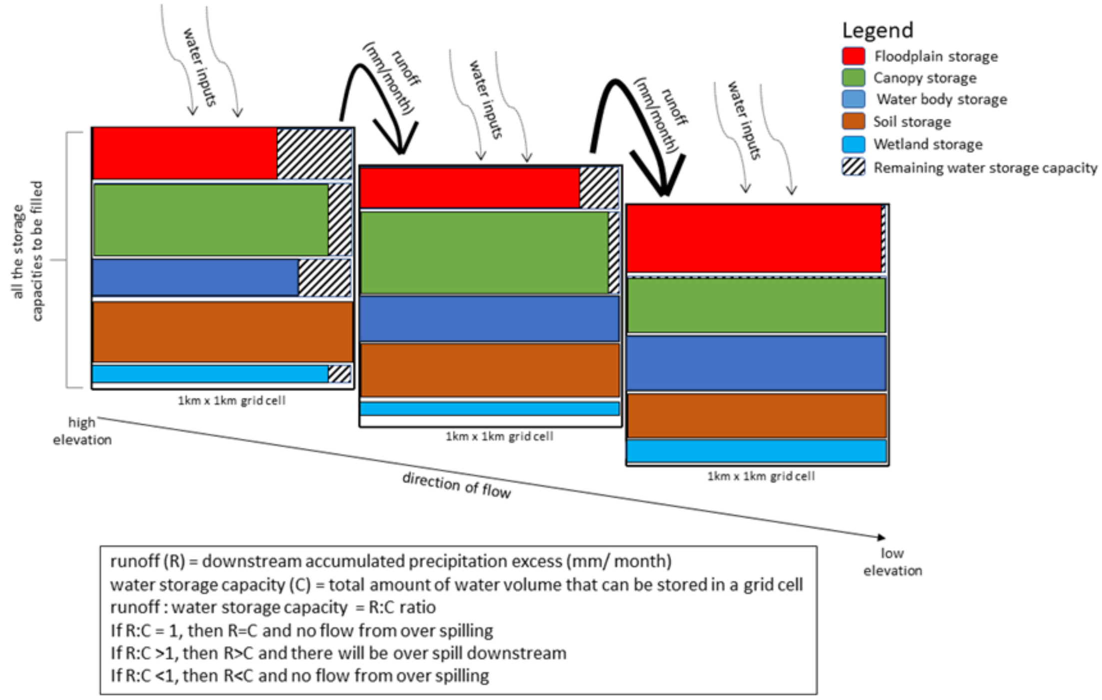

Figure 2. Natural infrastructure provides different types and sizes of water storage capacity in the landscape. Runoff occurs when the downstream accumulated water balance is greater than all the stores. The relationship between runoff and water storage capacity can be expressed as a ratio with values above unity indicating greater flood risk and values at unity or below, indicating lower flood risk.

Calculating protected and urban storage

As green storage can be influenced and modified by land cover and land use change, it is more vulnerable than blue storage. Protecting upstream green storage is thus important for basins upstream of cities to maintain existing storage potential and possible flood buffering. Here we used WaterWorld's (Mulligan 2013) calculation of green storage, the MODIS Urban Land cover 500m dataset (Schneider et al., 2009) and a protected areas dataset (IUCN & UNEP-WCMC, 2015) to show and calculate where and how much blue storage lies in urban areas and how much green storage lies within protected areas. We calculated what percentage of the protected storage accumulates downstream by dividing the accumulated protected total storage by the accumulated total storage and multiplying by 100. We also used the same urban dataset to calculate how much of the blue storage upstream of the selected cities falls within urban areas, as these indicate urban areas that lie in floodplains.

Results

Storage capacity of natural infrastructure in upstream basins

Table 1 summarises key water (storage capacity, rainfall, water balance), landcover (tree cover) and urban metrics for each of the city upstream basins calculated from WaterWorld (except where indicated).

Table 1. Comparison of area, water and urban metrics for each city upstream basin.

City upstream basin	Basin area (km^2)	Total water storage capacity (km^3)	Total rainfall (km^3/yr)	Total water balance (km^3/year)	Mean tree cover (%)	Urban area in upper basin (km^2)	Upstream basin population (number of people)	Upstream basin population density (people/km^2)	City population* (millions of people)
Chennai	1188.69	0.62	1903	253.8	6.6	94.48	1,518,610	1277.55	9.7
Jakarta	2340.65	0.96	2099	17030.66	27.7	367.02	4,839,840	2067.73	10.1
Bogotá	2509.25	0.99	6920	5636.21	15.3	86.57	972,496	387.56	9.7
London	6939.35	6.53	98768	81507.03	16.4	549.71	5,488,530	790.93	8.6
Guayaquil	32793.98	12.97	1973523	1534795.33	23.1	215.7	2,657,850	81.05	2.7

*UN (2018) for year 2015

Although the Jakarta upstream basin and the Bogota upstream basin are similarly sized, Jakarta receives three times more rain and has a third larger water balance. The Guayaquil upstream basin is 4.7 times larger than the London upstream basin and receives nearly 20 times more rain (due to its tropical climate and location near the equator). Although the London upstream basin has only slightly more (1.1 times) people living in it than the Jakarta upstream basin, the Jakarta upstream basin has a much higher density of people at 2067 people/km^2, compared to London's 790 people/km^2.

Water storage capacity for individual natural storage components across all five basins show that canopy accounts for the greatest storage capacity, followed by soil, floodplains, water bodies and wetlands (Figure 3a). However, these figures will be affected by basin size. The largest basins (Guayaquil and London) haver larger overall storages. Stores that predominate in those basins will influence the overall pattern. To remove the effect of basin size, the total storages were divided by the number of grid cells in each basin to get a mean storage capacity per grid cell per storage component for each basin (Figure 3b). This shows the same pattern but with different magnitudes; canopy is still the greatest storage across all the basins at 35.2% but is very closely followed by soil storage at 34.8%, a much smaller margin than when considering the sum storages.

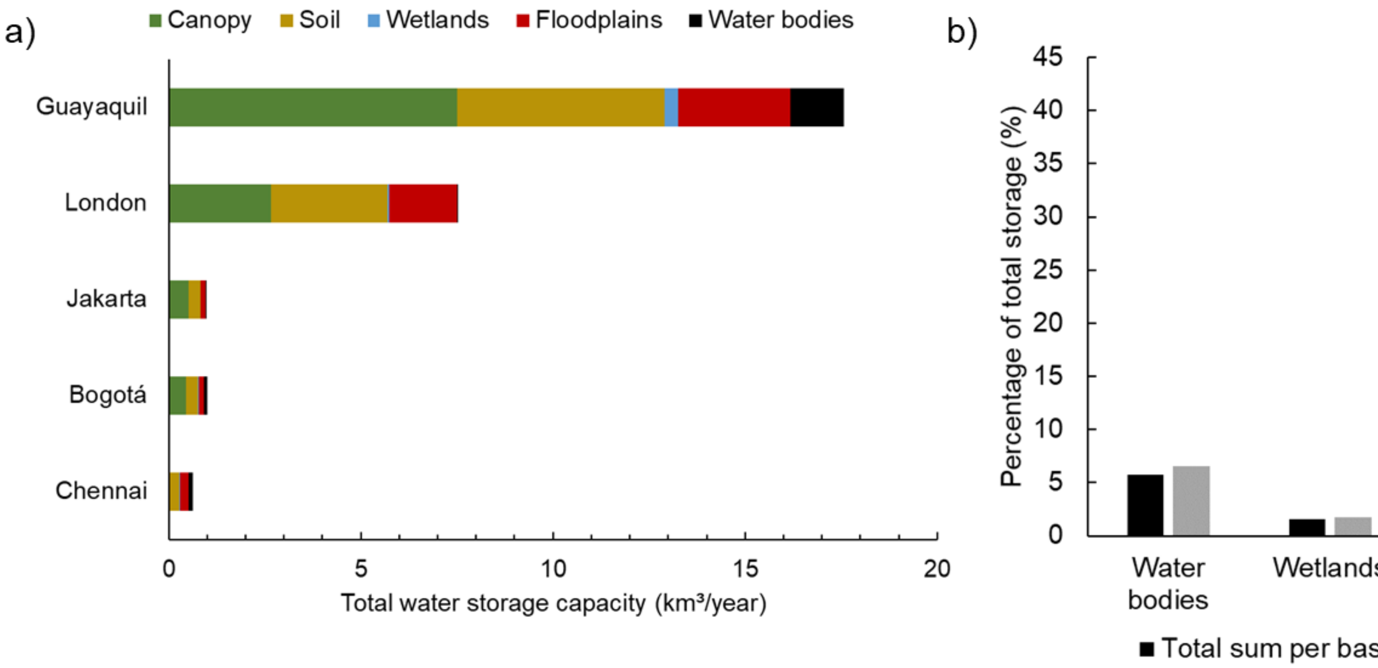

Figure 3. Natural Infrastructure storage capacities for five city upstream basins, a) showing the partition of storage type per city upstream basin, and b) showing the percentage of the total sum vs total mean (average per grid cell) storage that the storage components comprise for all basins.

Categorising the catchment mean storages into green (canopy, soil and wetlands) and blue (floodplains and water bodies) storage capacity, shows that green storage capacity is greater than blue capacity in all cases, except for the Chennai city upstream basin (Figure 4). Mean blue storage capacity is highest for Chennai (0.00023km^3) and lowest for Jakarta (0.00005km^3). However, of more interest is the relative proportion of green to blue, as green is more vulnerable to impacts of land use change or management than blue is.

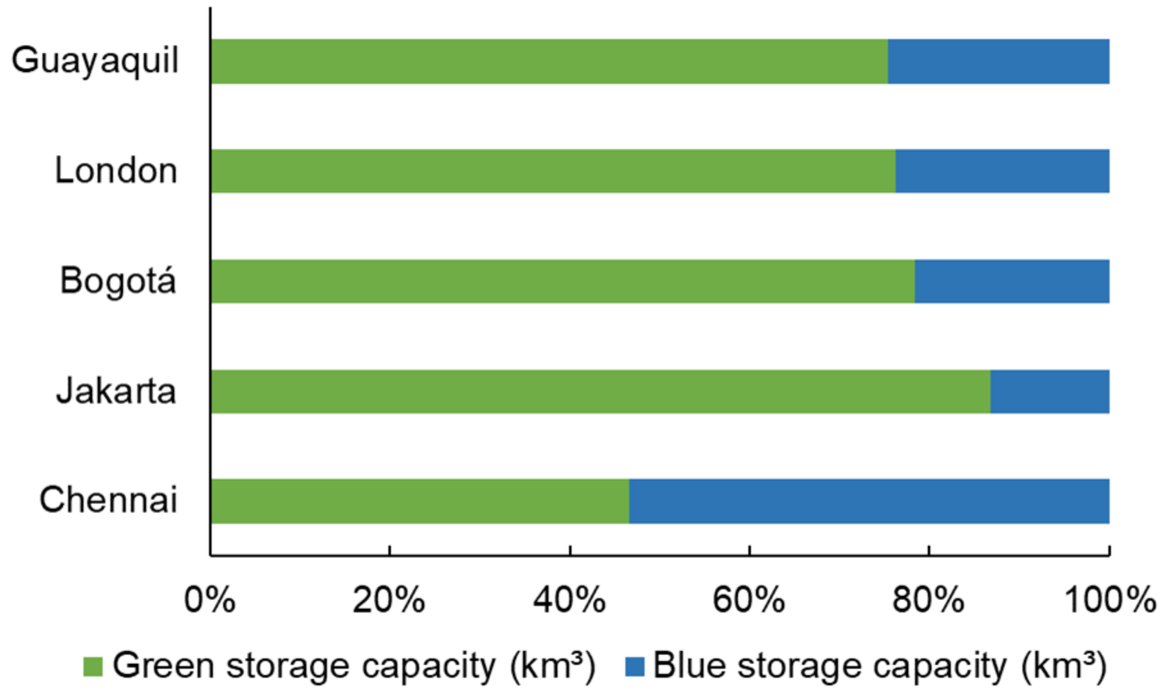

Figure 4: Proportion of mean green to mean blue water storage capacity, ordered by increasing basin size.

For four of the five basins, green storage was at least two-thirds greater than blue storage. Jakarta has the highest proportion of green storage at 86.7% of the total water storage capacity. The exception is the Chennai city upstream basin, which has greater blue storage than green, at 53.4% blue compared to 47.6% green.

Geographic location and distribution of natural storage components

To investigate the spatial distribution of natural storages for each city upstream basin, the storage that was dominant in each grid cell is mapped by WaterWorld (Figure 5). Even if one of the storage components is marginally greater for that grid cell, it will show as dominant. In other words, the greatest storage capacity does not have to be very large, just larger than the others. This is useful for indicating how, geographically, the most important storage types vary.

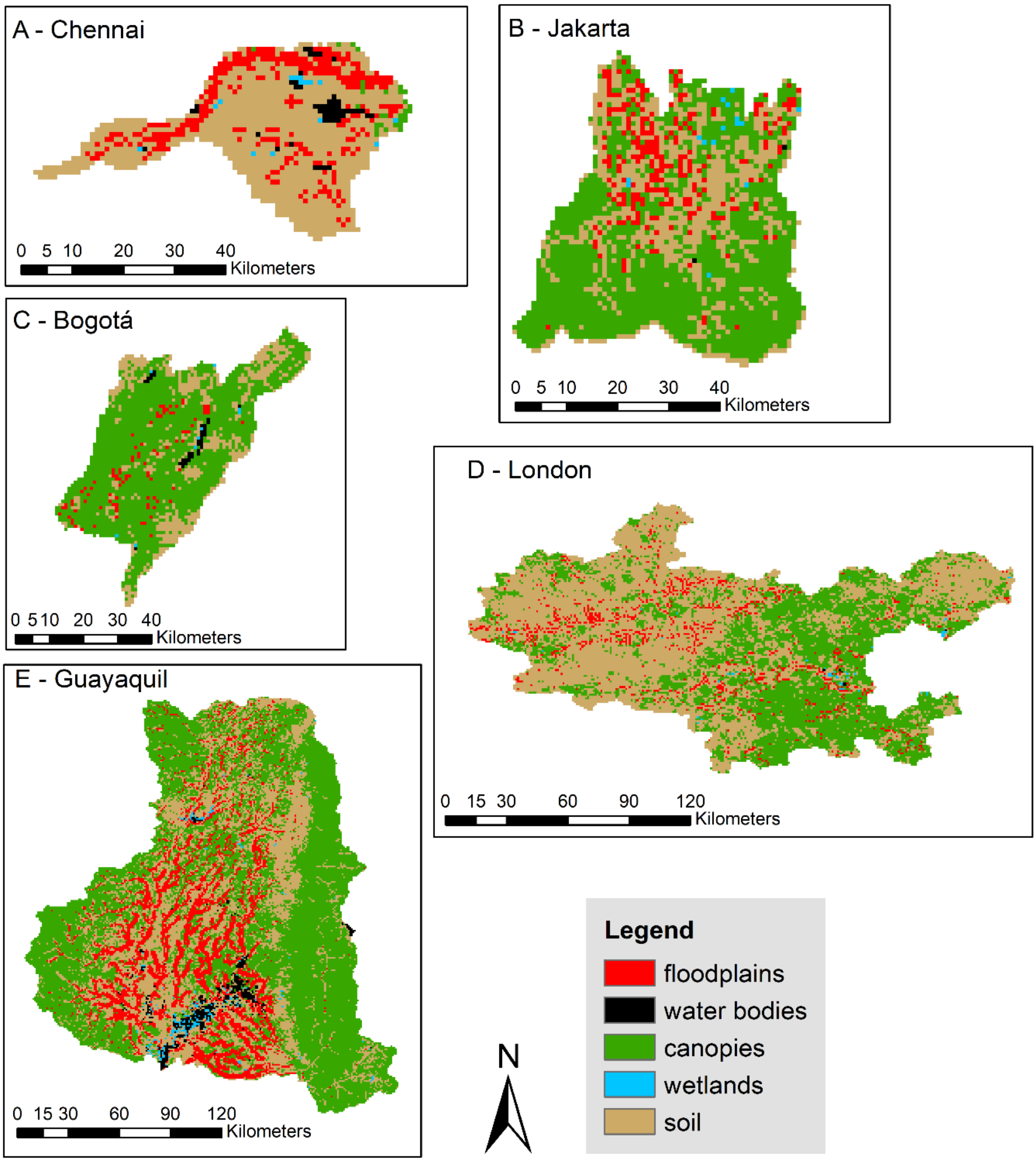

Figure 5: Spatial patterns and geographic distributions of dominant NI storage type for upstream city hydrological basin

Chennai is characterised by a lack of canopy storage at only 4.1% of the total storage and hardly any predominating except on the eastern edge closest to the city (Figure 5A). Soil and floodplains make up most of the water storage, at 38.5% and 38.2% respectively and are distributed across the basin. Water body storage is at 15.3% and wetlands 3.9% of total water storage capacity.

Jakarta has an uneven distribution of soil and canopy storage predominating, with canopy (52.8%) greatest to the south of the city in the uplands and soil (33.4%) greatest towards the coast (Figure 5B). Floodplain storage (13.2%) is also greatest to the north and west while wetlands (0.5%) are to the north and east. Waterbodies only account for 0.1% of total storage.

In the Bogotá upstream basin, the greatest storage comes from the canopy (45.7%) which is distributed throughout the basin, followed by soil storage (31.4%) (Figure 5C). Soil storage is greatest along the boundaries of the basin and in the northern higher elevations. Floodplain storage makes up 14.5% of the total and is greatest to the west of the basin and the centre. Waterbodies account for 7.2% and wetlands 1.2%.

Most of the water storage in the London upstream basin occurs in the soil (40.4%) and canopy (35.3%). The canopy storage is greatest around the city and towards the south. Soil storage predominates in the north and west of the basin (Figure 5D). Floodplain storage (23.6%) is evenly distributed throughout the basin. Water body (0.2%) and wetland storage (0.5%) is very limited.

The Guayaquil upstream basin shows canopy responsible for the most storage (42.7%) along the western edge and eastern edge of the basin (Figure 5E). Soil (30.7%) and floodplain (16.6%) storage predominates in the middle of the basin. Wetland (2%) and waterbody (8%) storage dominates in the lower part of the basin.

Protected storage

The amount of green storage within protected areas, either national parks or other forms of designation was calculated. London has the greatest amount of green storage protected at 33%. This is mostly made up of three Areas of Outstanding Natural Beauty (AONB), the Chiltern Hills AONB, the

North Wessex Downs AONB and the Cotswolds AONB. AONBs are areas designated for the purpose of conserving and enhancing their natural beauty where more consideration is needed by planning authorities for new development but doesn't mean that no new development occurs.

The next greatest green storage protection is the upper Bogotá basin with 12.5% and then Jakarta at 9.68%. Of concern is the Chennai city upstream basin, which has none of its green storage in protected areas. This is perhaps not surprising since India as a country has only 4.89% of its land protected. The Guayaquil upstream basin, which has just over three times more green storage than blue storage, has only 0.85% of this green storage protected. This is potentially concerning considering the very large size of the upstream basin and the fact that the Guayaquil city upstream basin is the least urbanised of all the watersheds. Most of the land use in this basin is agricultural. Ecuador's protected areas tend to be in the far eastern part of the country (Amazon), in the Andes mountains or along the coast.

We used the corresponding WaterWorld metrics to examine the flow and spatial configuration of protection by i) comparing the greatest accumulated protected storage, and ii) what percentage of total storage volume is protected as it accumulates downstream (Figure 6). The greatest accumulated protected storage tells us what type of storage the protected storage comes from as it accumulates downstream. For instance, in Bogotá, Jakarta and Guayaquil, it is the protected storage that originates from canopy upstream that is greatest and dominates as the storage accumulates downstream (Figure 6a). In the London upstream basin it is soil storage, with canopy storage dominating further downstream. So even though the most important functional storage may be the floodplains, the protected storage is of canopy or soil storage y. Besides a few places in the London upper basin, none of the basins show floodplain storage as the dominant storage protected. This has implications both for the volume of storage and for flood risk to human infrastructure placed within this storage (i.e. on floodplains).

The percentage of total storage volume that is protected shows, for all basins, a decay of the fraction protected as the storage accumulates downstream towards the city (Figure 6b). Even though most of the flood risk may be realised in the downstream more urbanised reaches, very little of the accumulated storage to these areas is protected with most of the protected storage occurring in the remote, most upstream parts of the basin.

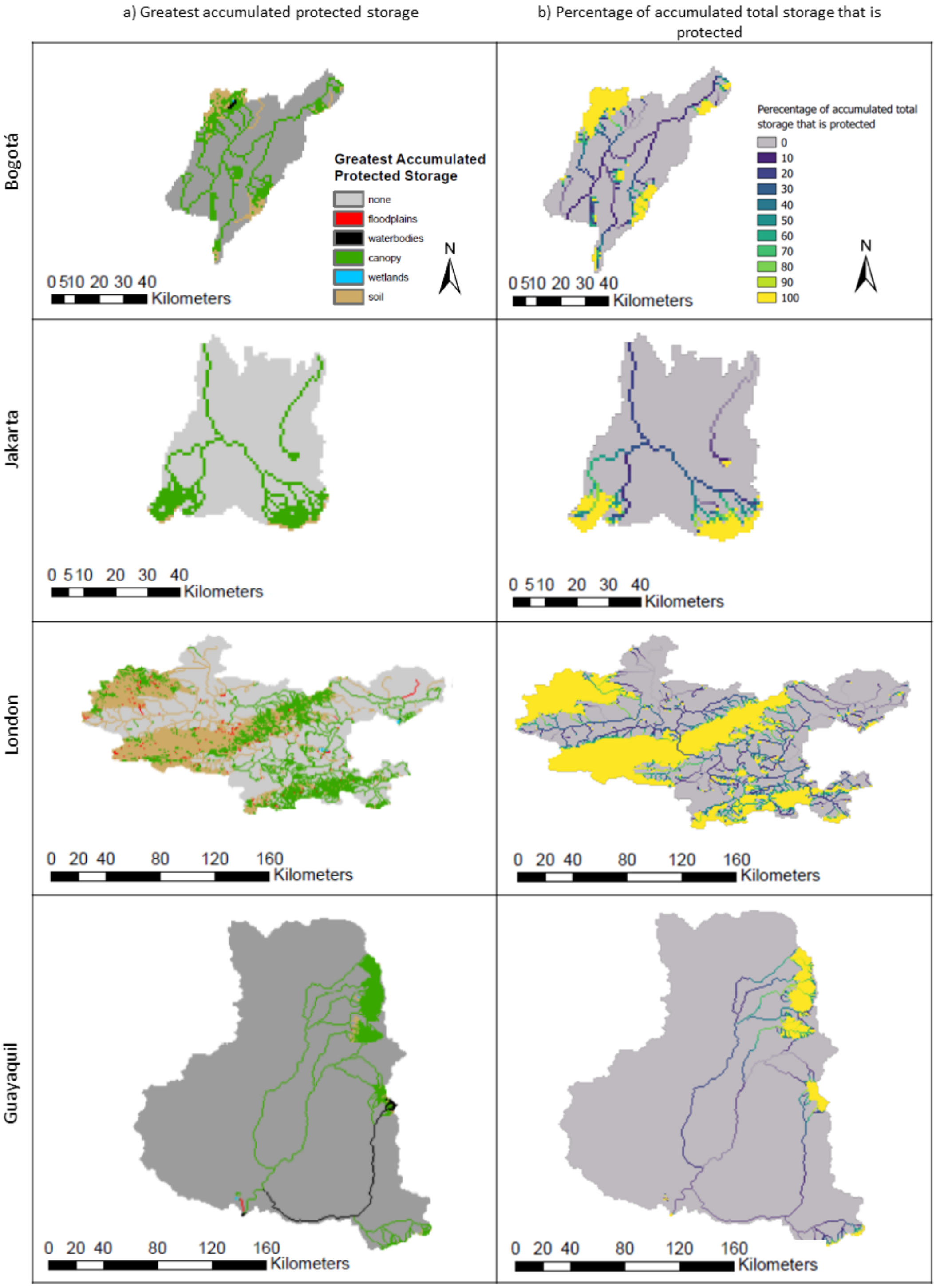

Figure 6. a) The greatest accumulated protected storage showing the dominant type of storage the protected storage comes from as it accumulates downstream, and b) the percentage of the total storage volume that is protected, shown for four of the five city basins. Chennai was excluded as none of its storage is protected.

Urban water storage

Of the five city upstream basins, Jakarta, is the most urbanised at 15.7% (Table 3). London and Chennai have similar levels of urbanisation at 7.92% and 7.95% respectively, just over half that of Jakarta. The percentage of blue storage volume that lies in urban areas was determined as these indicate urban areas that lie in floodplains (Table 2). Although less than 1% of the upper Guayaquil basin is urbanised, 6% of the blue storage volume in the basin overlies urban areas. The urbanised part of the Chennai upstream basin was almost all coincident with blue storage.

Table 2. Percentage of city upstream basin catchment, and blue storage volume, that is urban. i) Calculated by dividing the urban area in the upper basin by the total area of the upper basin, and ii) by dividing the urban blue storage by the total blue storage for the upstream basin

	Chennai	Jakarta	Bogotá	London	Guayaquil
i) % of upper catchment that is urban	7.95	15.68	3.45	7.92	0.66
ii) % blue storage volume in urban area	7.65	0	0	0.21	6.28

Spatial distributions of accumulated flood risk NI service

The WaterWorld surface water storage to capacity ratios were extracted for each city basin, to show the spatial distribution of potential flood risk. Values greater than 1 indicate likelihood to overspill on an annual basis since annual runoff is greater than available flood storage and, as is common, if this runoff were to occur in temporal clumps rather than evenly over the year, the storage may be overcome.

Ratio values less than 1, are unlikely to overspill on an annual timeframe (Figure 7). In these areas the storage types are under-utilised and have extra capacity to cope with increased water inputs.

The upper basin of Chennai shows a patchwork of cells with potential to flood (Figure 7A), mostly of low value; 48% have values between 1 and 6. These tend to coincide with cells that have greatest storage in the soil category. Another 48% of cells have a value less than 1, indicating low potential to flood on an annual basis. The area most downstream, and thus in the urbanised area of west Chennai, has the highest values, up to a maximum of 23.

The Bogotá upstream basin shows that most of it has potential to flood on an annual basis. High value cells are located on the eastern edge and north-west of the basin in the high mountain areas, as well as in the downstream urban area closest to Bogotá and the town of Chia (Figure 7B).

Almost every cell in the upper Jakarta basin has a value greater than 1, indicating potential to flood on an annual basis (Figure 7C). The Jakarta basin shows a wide spread of values with 96% of the values between 2.2 and 21, with a mean of 7.05. Areas of relative high value occur in the uplands adjacent to rivers with either soil or canopy supplying the greatest storage. The areas with the highest values are at the southernmost boundary of the basin, which is at the top of the watershed on the slopes of the volcanoes, and in the urban areas of Bogor and Depok.

Large areas of the London upper basin do not show ratios greater than 1, indicating that they have capacity to store the accumulated downstream precipitation (Figure 7D). The areas that do show potential to flood appear to be in W-E horizontal bands, adjacent to areas of high floodplain storage. 96% of the grid cells have relatively low ratios of between 1.2 and 2.2. Areas showing the highest ratios (and thus most potential to flood) coincide with urban areas such as Reading, Swindon, Basingstoke, Oxford, Maidenhead, Slough, Luton, Hemel Hempstead, Welwyn Garden City, and areas immediately west of London, such as Hounslow and Heathrow Airport. This reflects the fact that they have low tree and soil storage (being largely covered by concrete). Of course, the greater threat to flooding in London is from sea level rise and tidal surge combining with high flows on the Thames.

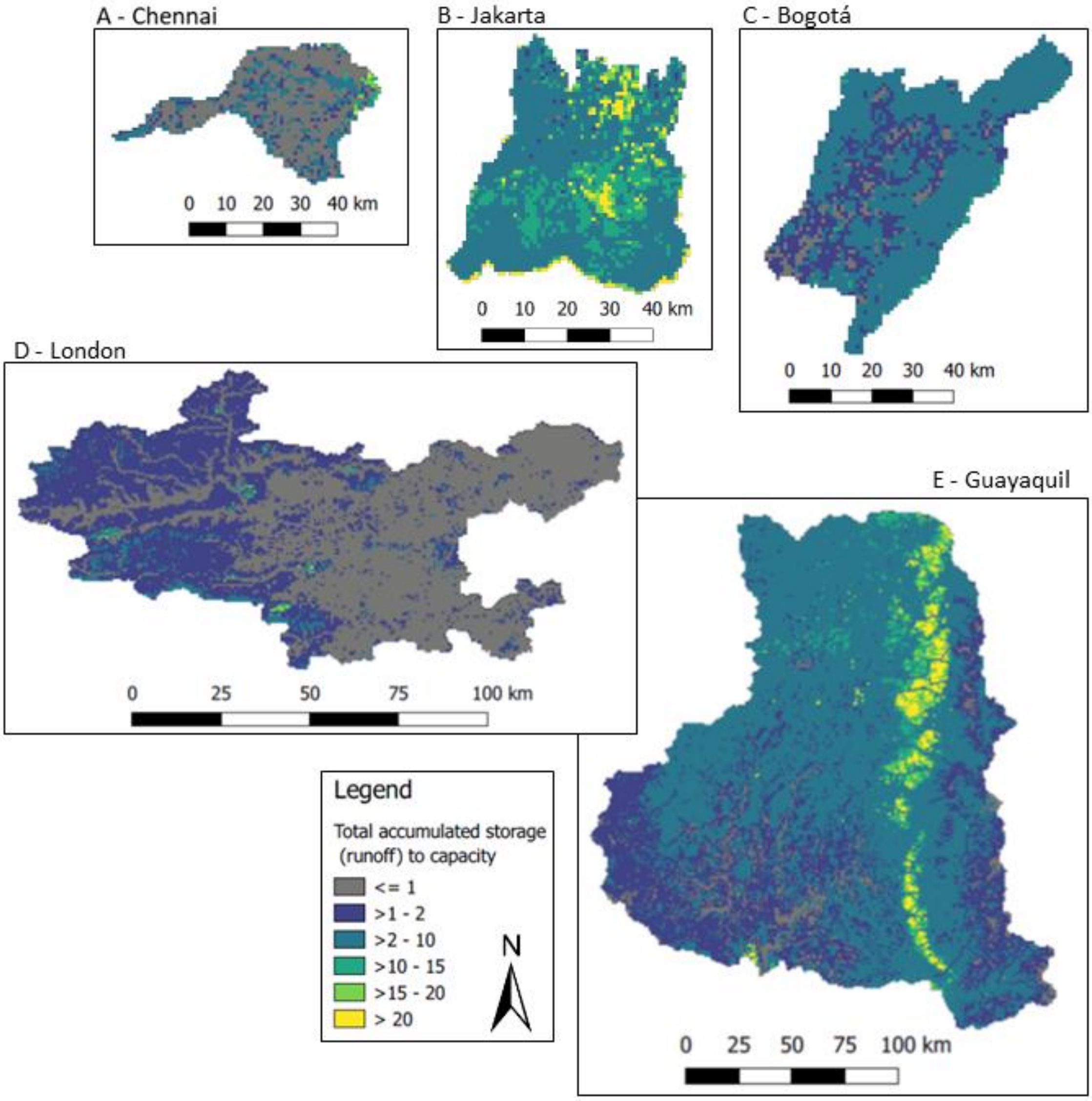

Figure 7. Spatial distribution of ratios of accumulated runoff to capacity for each of the upstream city watersheds (A - Chennai, B - Jakarta, C - Bogotá, D - London, and E - Guayaquil).

In the Guayaquil upstream basin, 95% of cells have values between 1.7 and 14, with a mean of 4.4 (Figure 7E). In the lower part of the basin are areas with values less than 1, showing capacity to store the water. These appear to be areas of water body storage. Extreme high values occur on the slopes of the Andes Mountains in the western part of the basin. High values also occur in the urban area of Quevedo and in the northern parts of Guayaquil at the bottom of the basin. Of all the cities, Guayaquil has the most extreme high values with max values up to 54. This is probably due to the high rainfall that occurs in the Andes Mountains.

Which storage component is providing the realized mitigation?

Separating the accumulated storage to capacity ratios into accumulated green and blue storage to capacity ratios is useful for telling us which storage type is providing the realized flood mitigation, i.e. flood mitigation where runoff is high enough for it to be necessary (Figure 8). The Chennai upstream basin shows a widespread mix of green and blue values over 1, mixed with widespread areas of values under 1 (Figure 8A). It appears that both green and blue are contributing fairly equally to flood mitigation throughout the basin.

In the Jakarta upstream basin it is green storage that is providing most of the flood mitigation but blue doing the work along the rivers, with hardly any areas below 1 (Figure 8B). In the Bogotá upstream basin, it is the green storage that is providing the flood mitigation, with thinly localised areas of blue providing storage along some rivers, adjacent to areas below 1 (Figure 8C). The London upstream basin is quite different to the others as it shows a west-east divide, with green storage dominating in the west half of the basin and the east half mostly being below 1, so not overspilling. Realized blue storage is found evenly on both sides along the river networks (Figure 8D). The Guayaquil upstream basin shows a fairly even mix of green and blue storage providing the flood mitigation, with green dominating on the eastern hillslopes and blue dominating towards the centre and west but distributed from north to south through the valley (Figure 8E).

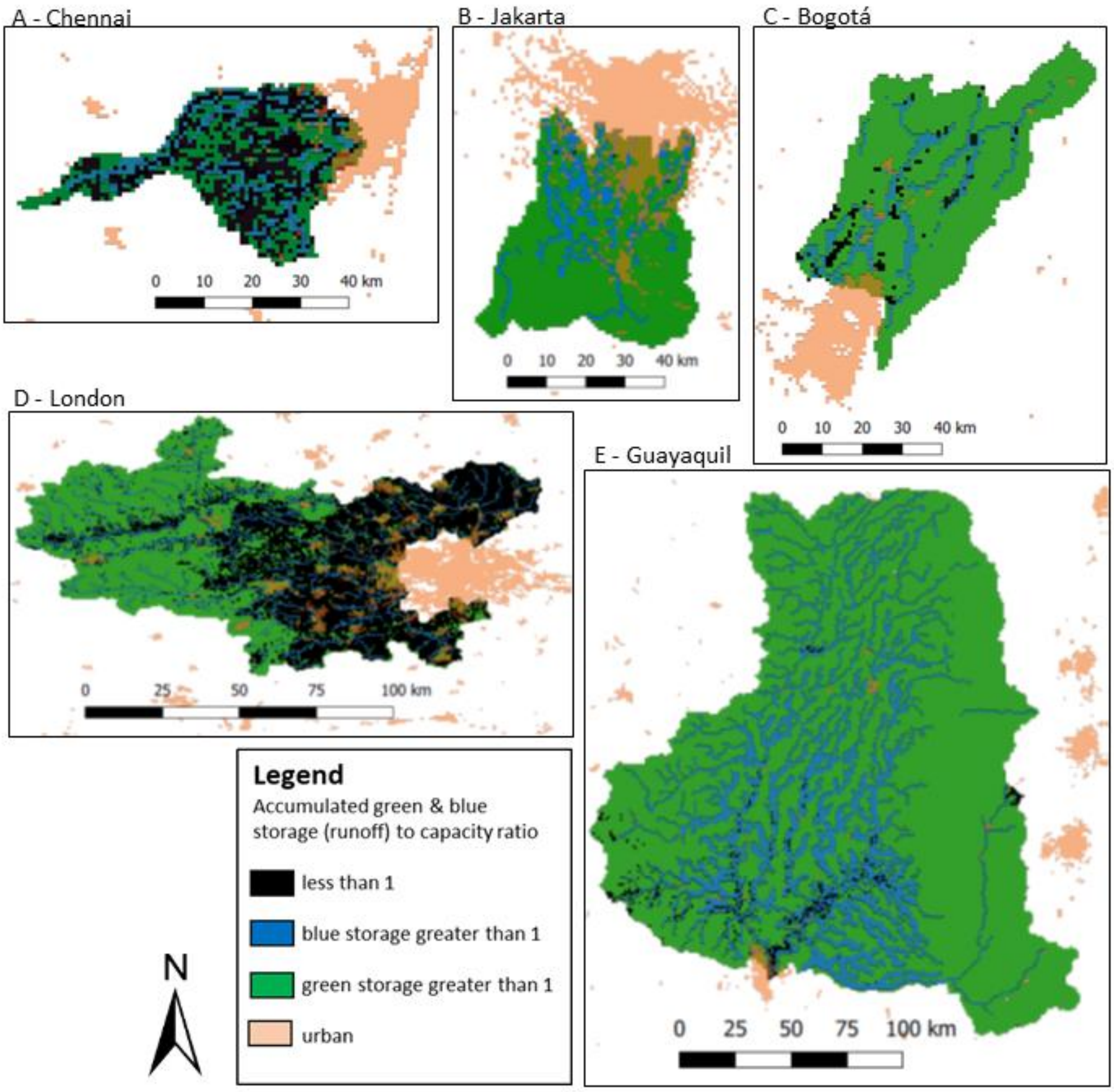

Figure 8. Spatial distribution of the accumulated storage (runoff) to capacity ratios greater than 1 (indicating flow) and less than 1 (no flow) for both green and blue/blue infrastructure.

Comparing annual cumulated runoff to storage capacity as potential flood risk ratios shows differences in the spatial distribution and overall pattern of green and blue mitigating storage, and areas of high and low flood risk. The patterns are summarised in Table 3; highlighting the dominance of either green or blue storage type, as 'heavy' or 'green-blue hybrid' if relatively spatially dispersed, and the spread of low-risk values as either 'dispersed' or 'concentrated', based on visual observation of Figure 8. Each pattern-type may suggest a different strategy for improving or enhancing flood risk mitigation through natural infrastructure storage.

Table 3. Summary of the city upstream basins' flood risk patterns.

Upstream basin	**Natural storage and potential flood risk pattern**
Chennai	Green-blue hybrid; low-risk dispersed
Jakarta	Green heavy; low-risk dispersed
Bogotá	Green heavy; low-risk dispersed
London	Green heavy; low-risk concentrated
Guayaquil	Green-blue hybrid; low-risk concentrated

It is worth noting that these ratios and associated patterns are based on average annual values and provide a broad picture; at a finer temporal resolution individual events may cause flooding that show different patterns and trends that are more to do with the size and distribution of the event than the patterns of available storage.

Discussion

Characterisation of the different types and magnitudes of natural flood storage

Landscapes vary in their ability to store water with the variability largely due to differences in topography, soil depth and condition, number of water bodies including rivers and lakes, and also land cover and land use, affecting canopy cover and soil characteristics (as seen in Figure 5). The ability to quantify the storage capacity and evaluate the distribution of these natural infrastructure components by city upstream basin should enable us to characterise the city upstream basin's potential to store upstream precipitation excess and thus flood risk.

In this paper we propose that categorizing natural flood storage as either 'green' or 'blue' based on ability to be influenced by human activity, and determining the size of the relative contribution of green and blue storage to total storage, indicates the level of vulnerability to modification of the upstream water storage and flood buffer. If the water storage is skewed in favour of green storage (canopy, soil, wetlands), which is vulnerable to human modification, then it can be altered (lost or enhanced) due to land conversion or reclamation, which may influence downstream exposure to flood risk.

Indeed, our analysis revealed a strong reliance on green storage. For three of the basins (Bogotá, London and Guayaquil) there is three times more green storage than blue. Jakarta had 6.5 times more green than blue storage. This strong skew towards green storage may be surprising to those who consider blue storage and grey infrastructure (reservoirs) the most significant for flood mitigation. Our results highlight the value and importance of green storage in these systems emphasising the need to appropriately value and preserve them. These findings agree with those from other studies. Nedkov and Burkhard (2012) also found that land cover classes with higher vegetation cover (i.e. forests) have higher flood regulation capacities due to their higher ability to “catch” part of the incoming water from precipitation. Stürck et al. (2014) found that regions with a high capacity to provide flood regulation are mainly characterized by large patches of natural vegetation or extensive agriculture. Fu et al. (2013) found that the flood mitigation function for forests, grasslands and other terrestrial ecosystems was significantly higher than that for lakes, reservoirs, marshes and other wetland ecosystems.

Contrary to the other basins, Chennai had more blue than green storage. The volume of canopy storage appears to be what drives this pattern, reflecting the lack of tree cover in the basin. For the green-heavy basins, between 35 and 54% of their storage was in the canopy while Chennai only has 4% of its storage in canopy storage. The strong influence of canopy storage for some basins is most likely due to its wide coverage across the landscape, and that this store empties to the atmosphere after rainfall events so can be refilled without emptying downstream to the rivers. It is likely that historically Chennai’s canopy cover, and thus green storage, was greater but has declined due to land use change. A temporal analysis may be of interest to see how the green and blue storage has changed over time.

Soil (part of green storage) was also a large part of the overall storage, accounting for 33.6% of the total storage on average across the basins. Unlike canopies, when soil empties it drains largely to throughflow and baseflow (thus generating runoff). Stürck et al. (2014) concluded that the main factor limiting flood regulation supply on a continental scale is low water holding capacity of the soil.

Water bodies and wetlands are commonly associated with water storage but are rather intermittent in landscapes and so have a relatively small overall storage capacity among our basins, at 5.7% and 1.6% of the total storage, respectively. This has also been observed in application of these WaterWorld metrics around the world. Many wetlands tend to be fairly small, and it may be the case that they were not picked up by the resolution (1km) of the MODIS imagery. However, the size of wetlands has been shown to be important in their capacity to provide flood mitigation. If wetlands are too small, functions such as storage of floodwater, no longer exist. It has been assessed that 3–7% of the area of a watershed in temperate zones should be maintained as wetlands to provide both adequate flood control and water quality improvement functions (Depietri et al., 2012; Mitsch and Gosselink, 2000). Although it is difficult to create new waterbodies, other than through building dams, the creation of new wetland storage may be an important tactic to increase overall flood storage to specific sites downstream.

For Chennai, the relatively large volume of blue storage in the system indicates a possible opportunity to increase flood storage by increasing the amount of green storage, particularly through soil conservation measures, but also through wetland creation and restoration. Any strategy aimed at mitigating flood must also ensure that dry season flows are maintained and water resources are not compromised.

Determining how much is 'secured' in protected areas or 'at risk' in urban areas

Due to the vulnerability of green storage to modification it is important to downstream users that upstream green storage is protected. Our analysis showed that very little (0-32%) of the green storage in the five city upstream basins is protected. The storage that is protected tends to be remote and in high elevation areas resulting in significant distance between sites of service provision and of potential benefit. Also, the level of protection may not be adequate, such as the AONB's in the London basin, to deter the kinds of land modification that could affect storage.

Criteria for choosing where to designate a protected area (PA) has historically been based on aesthetic and socio-economic concerns (Leader-Williams et al., 1990; Pressey, 1994), and more recently by levels of species-richness or degrees of 'naturalness' (Dudley, 2008). Most PAs tend to over-represent high elevation areas and other regions with low agricultural potential (Oldfield et al., 2004) reflecting also the role of low land prices. PA location is rarely based on its utility for providing flood regulation services.

We propose that provincial and city authorities liaise with relevant organisations, and in open consultation with all relevant stakeholders, to secure more of their upland green storage from land use change and development by designating these areas as protected, or placed under stewardship schemes, that are focused on natural flood management. Many of the service-providing areas are agricultural and affording protection will require engagement with farmers. Policy and stakeholder analysis in each catchment should be explored in further policy-science or governance research. However, it is not just the green storage that needs protection. Our analysis showed that barely any floodplain storage was protected. Floodplains are extremely important for providing a flood buffer but also tend to be built upon, increasing the exposure to flood risk. Where significant flood storage occurs on floodplains within the urban fabric, for this storage to be utilised, exposed assets (buildings and infrastructure) are flooded.

Targeting areas for protection, restoration or enhancement of flood mitigation interventions

Our analysis and the method described could assist in determining the amount and locations of the green storage to be protected, restored or enhanced. We propose to prioritise areas for intervention upstream of where:

1) Accumulated green storage to capacity ratio is greater than 1 (but not so much greater than 1 that intervention to bring the ratio to 1 would not be feasible). The >1 to 2 ratio classes shown in Figure 7 may be a good starting point to target initial interventions.
2) Accumulated protected storage at cities is low (e.g. such as demonstrated in Figure 6) and thus storage is vulnerable.
3) Areas are urban or heavily populated and thus have low land prices.
4) Areas with the potential for one of a variety of interventions, including soil management, afforestation, wetland restoration etc.

Decisions for each region will require use of detailed land-cover/land-use maps and property value information; this study has made the first step but has primarily demonstrated the use of accessible and freely available global metrics that can be applied consistently across basins for preliminary assessments.

NFM interventions generally aim to achieve three things: 1) reduce rapid runoff generation and retain water in the landscape through management of infiltration, 2) reduce river and floodplain conveyance, and 3) increase water storage. Practices to achieve reduction of runoff and increased infiltration include land-use changes, changes in arable land-use practices, changes in livestock land practices, changes in tillage practices, field drainage (to increase storage), creation of buffer strips and buffer zones, machinery management (such as low-ground pressures and avoiding wet conditions), urban land-use changes (such as permeable paving) and afforestation (Dadson et al., 2017; Lane, 2017). Practices to reduce river and floodplain conveyance are focused on reducing hillslope-channel coupling (the connections between the stream channel and the hillslope and between the channel and the upstream reaches) e.g. by blocking drains; management of riparian conveyance, by increasing river and floodplain roughness, and realignment and restoration of river channels (Dadson 2017; Lane 2017). Water storage can be increased i) upstream, such as ponds, bunds and ditches; wetlands and washlands, impounded storage; and ii) in the floodplain, such as through floodplain restoration (Dadson 2017; Lane 2017).

However, the impact of NFM interventions on flooding is increasingly being shown to depend on i) the scale of the measure, ii) the size of the catchment on which the measure is being implemented, iii) the location within the catchment, and iv) the connectivity of the channel network (Iacob et al. 2014, Dadson et al. 2017). For example, Dadson et al. (2017) found in their review that there is clear evidence that appropriately chosen land-use and land-cover interventions can reduce local peak water flows after moderate rainfall events and in small catchments. However, the evidence does not suggest these interventions will have a major effect on nearby downstream flood risk for the most extreme events or in large catchments. Our study basins are in large catchments, but the flood risk maps we present show the likelihood to overspill on an annual basis. If additional storage can be created to cope with the annual runoff so that it does not overspill, then there is also a greater chance of dealing with flooding during extreme rainfall events.

Impacts of land use and population change on the capacity of natural flood management infrastructure

This study has particular relevance in highlighting the role and lack of protection of green infrastructure, given the vulnerabilities of such areas to land use changes associated with nearby urbanisation. The urbanisation of the countryside, called peri-urbanisation, results from the migration of urban populations to rural areas for a better quality of life. Peri-urban areas are frequently subject to sprawl of urban and agricultural infrastructure associated with growing urban populations, and such sprawl will inevitably impact on areas of green storage infrastructure unless steps are taken to protect these areas and/or mitigate impacts. Key land use changes associated with sprawl include removal of vegetation (canopy storage), compaction or destruction of soils (soil storage) and drainage of wetlands. Likewise, the drive for greater productivity in farming has led to agricultural intensification which includes landscape changes such as the loss of hedgerows and an increase in field size, the installation of land drains connecting hilltop to river channel, and channelised rivers with no riparian zone (Wheater and Evans, 2009). In this way, changes to land use associated with increasing urbanisation and agricultural intensification, are likely to significantly negatively impact water storage capacity, flood regulation and other ecosystem services, and the results presented here indicate that key areas of concern around major cities can be highlighted for further consideration and potential conservation and restoration actions.

Significance of Natural Infrastructure flood risk metrics

We have applied simple but robust and globally applicable metrics based on remote sensed data to enhance understanding of flood risk and the role of natural flood management infrastructure across a range of cities. These metrics can be applied for any basin or country as part of the WaterWorld tool (Mulligan 2013; Mulligan 2016)(. They have the advantage of not requiring complex data gathering or processing so can be applied rapidly to new study areas in a way that is globally consistent and therefore comparable. They consider both the potential service (as the storage volume), the realized service (the storage volume in relation to the volume of storage required to store the annual runoff), the sites of service consumption (urban areas for this paper) and other characteristics of the service providing areas (e.g. protected areas for this paper). As simple globally applicable metrics, they do not incorporate grey flood mitigation infrastructure such as levees and flood control schemes (other than large dams). Nor do these metrics focus on flood events (since future rainfall magnitudes and distributions are essentially unpredictable). Rather the WaterWorld metrics focus on the extent to which the annual runoff is less than or greater than the flood storage capacity, in recognition that if there is sufficient flood storage capacity to hold the annual runoff then, all else being equal, flooding will be less common. Stores that drain to the land component of the hydrological cycle are not considered to have refill capacity within the year given that any drainage is to land stores downstream and thus represents flood risk; the only store that refills is the canopy storage that empties to the atmosphere and thus does not contribute to flood risk. Though we calculate a full water balance including evapotranspiration by agriculture, water extraction for urban domestic use is not factored in as this is not a consumptive use (water is returned through drains to the land system so is still available to cause flooding downstream).

Conclusion

We have demonstrated the application of WaterWorld's Natural Infrastructure flood risk metrics in the upstream basins of five cities that have differing basin characteristics and climatology. By mapping the magnitude and types of 'natural' storages in these basins, we have shown that most city upstream basins have a strong reliance on green natural storage which is driven primarily by canopy cover but also soil storage. This skew towards green storage means that major sources of landscape level water storage are susceptible to modification or removal, leaving those cities vulnerable to an increase in flood risk.

Indeed, when relating the storage to protected areas we discovered a widespread lack of protection for this valuable green natural storage. Some city upstream basins, such as Chennai and Guayaquil, have almost no protection of green storage areas. For those basins with some level of protection, these areas were often in remote high-elevation areas at considerable distance to the beneficiaries of the service.

The use of WaterWorld's accumulated annual runoff to storage capacity ratios to determine areas of potential annual flood risk revealed distinct patterns as to which storage was contributing to the flood mitigation and where it was located. These patterns could indicate that disparate city basins may be categorised into different 'storage/risk' types with associated strategies for intervention. Hence, such tools that allow rapid initial assessments of the contribution of natural flood infrastructure to mitigating flood risk in urban areas, across multiple cities at national, regional and even global scales, allows a diverse range of stakeholders, from city planners and protected area managers, to national governments and civil society organizations, to assess optimal locations for further, more detailed analysis, planning and investment in green flood storage.

Overall, we have shown that the method of comparing storage capacity to runoff volumes as ratios could be a useful way to determine potential flood hazard using globally accessible data inputs. This analysis was done using the default parameter values for the natural storage metrics across all five basins. However, practitioners working in specific locations could use their own parameter values, or even their own storage maps in the WaterWorld platform, to obtain more locally specific results. In particular, site specific information on soil types and depths could greatly improve the storage estimates.

The methods outlined here allow for the identification of priority areas for conservation of flood relevant natural infrastructure under current conditions and scenarios of land use and climate change.

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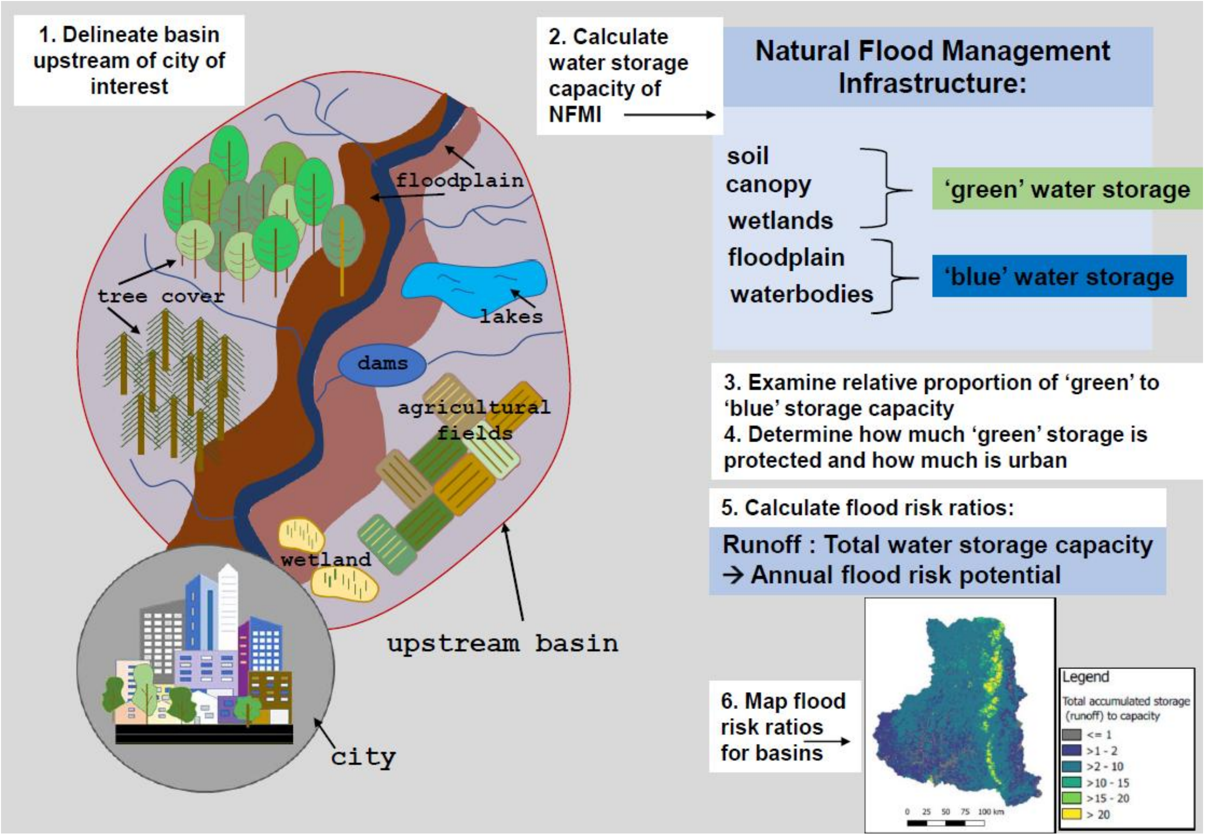
Graphical_abstract



Highlights:

- Natural water storage metrics are applied to upstream basins of five global cities
- Strong reliance on forest, soil and wetland storage is found in four basins
- Little of this storage is protected making it vulnerable to land-use modification
- The basins show different patterns of flood risk magnitude and spatial distribution